

HYDROLOGY AND HYDRAULIC BRANCH

REALLOCATION for WATER SUPPLY on CENTER HILL RESERVOIR, TENNESSEE

1.0. Purpose

The purpose of this document is to define the procedure used to evaluate requests to purchase water supply storage within Center Hill Reservoir.

2.0. Reallocation Theory

2.1. Consider the design of a "single purpose" water supply dam. If an entity designs such a water supply dam, a mass balance process is usually required to determine the project storage requirements that directly link to the size of the dam that is needed.

2.2. Sediment storage is typically accounted for first in the design process. Also, the design life of a district project is fifty years; however, Center Hill Dam and Reservoir is already fifty years old. It is calculated that Center Hill Dam and Reservoir will last another fifty years. The combined life expectancy will equal the sedimentation rate, typically one hundred years. It is also typically assumed to accumulate in the lower storage reaches of the impoundment area. It is computed as if the sediment layers (stacks) against the base of the dam. The lowest intake of the pipe used to withdraw water from the reservoir is typically designed with an invert elevation located a few feet above this hypothetical sediment pool. In reality, sediment typically forms a delta in the upstream limits of the reservoir impoundment. Over long periods of time the delta migrates towards the dam. If an intake is to be located in the upstream most limits of a reservoir, then additional sediment studies are often warranted to determine the lowest elevation that a water intake should be located. Since detailed sediment studies are often very costly, the conservative assumption of sediments stacking against the base of the dam is standard.

2.3. Enough water must be stored in the reservoir to assure that the water surface does not drop below the effective intake structure elevation. This is accomplished by evaluating a mass balance of all inflows and outflows (including water supply of a reservoir system).

2.4. Normal inflows to the reservoir system are rain dependent and include runoff and baseflow. Under ideal circumstances a long-term streamgauge is located upstream of the dam and records the inflows to the reservoir directly. Otherwise, inflows are estimated using gages in the region with similar hydrologic characteristics or by developing sophisticated hydrology models.

2.5. The normal outflows from a reservoir system are the withdrawals by the municipal & industrial (M&I) user, mandatory releases for water quality and/or for other contractual agreements, leakage, and evaporation. Leakage through the dam itself often provides sufficient flow rates to meet downstream water quality requirements. If not, then seasonal minimum daily outflow requirements are typically established.

2.6. For small drainage basins the flow in a stream can go to zero for periods of months during extreme droughts. For this condition, the water supply dam must provide stored water to offset these periods of zero inflow. If historically, there was a 120 day period of no flow at a damsite then the minimum storage requirement would be 120 times the average daily outflow (withdrawal + evaporation + leakage + water quality).

2.7. A water supply reservoir should be designed to provide enough storage to offset historically recorded times when the inflow is less than the outflow. If the historical period is less than 50 years, then stochastic methods should be used to develop frequency data. Consequently, this reservoir will always provide enough water to meet the designed needs for a continuous period of time as long as there is no drought greater than what has already occurred historically.

2.8. Using the mass balance concept noted above, the amount of storage that would be needed in any Cumberland River Basin reservoir to meet withdrawal demands through all historical drought periods could be determined.

3.0. Engineering Methods

The following paragraphs discuss the engineering methods used to arrive at the data presented in this study. This portion of the study also discusses any assumptions made and the sources of data that were used.

3.1. General Procedure:

3.1.a. To determine the most severe drought impacts upon the hydropower pool, special consideration must be given to the starting conditions within the hydrologic modeling process. The starting water surface elevation of the reservoir was assumed to be equal to the top of its hydropower pool elevation (648.0 feet). Several model runs were made to ensure that the model is started at a date (within a 15-day span) such that the hydropower pool continuously lowers during the drought period. This insures that no excess inflow to the reservoir is included in the drought period. An overflow is also set at the 648 elevation within the hydrologic model. This insures that any inflows that might raise the pool above the 648 elevation would not be stored in the reservoir.

3.1.b. Reservoir evaporation was first determined as monthly volumes. It was then converted to average monthly flows to allow subtraction

from the average monthly inflows. In some months this resulted in negative flows because there was more evaporation than inflow.

3.1.c. Leakage from a dam is the total amount of water passing through under and around the dam. The amount of leakage at any dam is an elusive quantity because there are so many unknown variables. Leakage at Center Hill Dam is estimated to be 90 cfs. It was assumed that a constant outflow represents leakage and water quality outflows. The leakage was represented in the model by a Low-Level Outlet (SL) card. This allowed a constant outflow of 90.0 cfs at the 648.0 foot elevation. It was assumed that an orifice located at the streambed with an area of 1.465 square feet was representative of leakage.

3.1.d. There are mandatory water quality releases of 80 cfs every other day for Center Hill Reservoir. Lake Cumberland, Center Hill Reservoir, and Dale Hollow Reservoir are used to provide a constant flow to the Cumberland River so that the dissolved oxygen levels below Old Hickory Dam are kept to a minimum level of 5.0 mg/l. Approximately 69% of the flow is contributed by Lake Cumberland. Center Hill Reservoir and Dale Hollow Reservoir contribute 16% and 15% respectively. **Table 1** shows the theoretical mean monthly minimum inflows needed at Old Hickory Reservoir and the theoretical mean monthly minimum outflows (releases) from Center Hill Reservoir.

Table 1
Theoretical Mean Monthly Outflows for Water Quality
for Center Hill Reservoir, Tennessee

Month of Year	Outflows to Meet Dissolved Oxygen Levels at Old Hickory (CFS)	69% Lake Cumberland (CFS)	15% Dale Hollow (CFS)	16% Center Hill (CFS)
January	0	0	0	0
February	0	0	0	0
March	0	0	0	0
April	1500	1035	225	240
May	4900	3381	735	784
June	7600	5244	1140	1216
July	9100	6279	1365	1456
August	9400	6486	1410	1504
September	7400	5106	1110	1184
October	1000	690	150	160
November	0	0	0	0
December	0	0	0	0

In addition to the water quality releases, the minimum Southeastern Power Agency (SEPA) requirements must be met for hydropower generation. During the summer months, the water quality releases are made through the turbines and are sufficient to meet the minimum power requirements. The same percentages of releases are used as were used for water quality. **Table 2** lists the minimum outflows for power.

Table 2
Mean Monthly Outflows for Hydropower
for Center Hill Reservoir, Tennessee

Month of Year	Outflows to Meet Minimum Hydropower Requirements from Basin (CFS)	69% Lake Cumberland (CFS)	15% Dale Hollow (CFS)	16% Center Hill (CFS)
January	6700	4623	1005	1072
February	7600	5244	1140	1216
March	8300	5727	1245	1328
April	8300	5727	1245	1328
May	5800	4002	870	928
June	6300	4347	945	1008
July	8300	5727	1245	1328
August	8300	5727	1245	1328
September	5400	3726	810	864
October	4100	2829	615	656
November	4200	2898	630	672
December	5100	3519	765	816

Because water quality releases are made through the turbines, the higher of the water quality or the hydropower releases was used. **Table 3** lists the mean monthly outflows for Water quality and Hydropower at Center Hill Reservoir.

Table 3
Mean Monthly Outflows
for Center Hill Reservoir, Tennessee

Month Of Year	Water Quality Center Hill (CFS)	Hydropower Center Hill (CFS)	Maximum Center Hill (CFS)
January	0	1072	1072
February	0	1216	1216
March	0	1328	1328
April	240	1328	1328
May	784	928	928
June	1216	1008	1216
July	1456	1328	1456

August	1504	1328	1504
September	1184	864	1184
October	160	656	656
November	0	672	672
December	0	816	816

The releases made at Center Hill Dam were entered as negative flows into a DSS file.

3.1.e. The critical, low-flow period (mid-July 1953 to Dec 1953) was then routed through the reservoir. The critical period was representative of the lowest recorded inflows actually occurring over the last 88 years.

3.1.f. The withdrawal rate from Center Hill Reservoir is fixed at the ten year anticipated future need for all M&I users, plus 10% for any new users. Three sets of conditions were used in the model to determine the minimum reservoir water surface elevation during the design drought period: 1) evaporation only; 2) evaporation with water quality or hydropower and leakage; and 3) evaporation, water quality or hydropower, leakage, and anticipated water supply usage to the year 2009. The storage required to meet the water supply demand is the difference in the lowest elevation attained without water supply and the one with water supply.

3.1.g. When additional withdrawals are requested which surpass the 10% set aside for new users, the same data must be used as a base for recalculating the inflow hydrograph and rerunning the mass balance model.

3.2. Evaporation.

3.2.a. Evaporation is a significant factor to be considered in the design of water supply reservoirs. The lowest inflows in the Cumberland River Basin have occurred during the months June through November. The inflows before and after the months of June and November are generally sufficient to fill the reservoirs to the top of their hydropower pools. Evaporation data is not needed for the period of time the reservoir is above its hydropower pool. A longer, more conservative period from June to February is used for this study to ensure that the reservoir returns to the top of its hydropower pool. A review of critical drought reservoir data supports these assumptions as being reasonable.

3.2.b. The evaporation for each month over the eight-month period (June - February) was determined from National Weather Service "Class A" pan evaporation data. During the critical period of 1953-1954, no evaporation data were available for Center Hill Dam. Therefore, the evaporation data was determined by using the United States Geological Service station at Center Hill Dam, near the dam, Latitude 36:06, Longitude 085:49, elevation 580.0 feet. This site was used for the period between 1964 and 1975. The maximum monthly rates recorded in this period by this station were used to simulate evaporation for the 1953 drought year. These evaporation rates and the associated

outflows are shown in **Table 4**. Evaporation rates were based on the highest values that actually occurred between 1964 and 1975.

Table 4
Evaporation Rates and
Evaporation Outflows for
Center Hill Reservoir

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max. Monthly Evap. Rates	1.97	1.85	4.76	6.05	6.37	7.66	7.54	7.07	5.48	4.35	2.53	1.50
Lake Hefner Class "A" Pan Conversion Factors	0.7	0.3	0.4	0.4	0.4	0.6	0.7	0.8	0.9	0.9	1.2	1.1
Adjusted Evap. Rates	1.38	0.56	1.90	2.42	2.55	4.60	5.28	5.66	4.93	3.92	3.04	1.65
Evaporation Rates as Outflows (CFS)	37	17	51	67	68	128	142	152	137	105	84	44

3.2.c. "Class A" evaporation pan data differs from actual lake evaporation. The difference was adjusted by multiplying the "Class A" evaporation data by Lake Hefner pan coefficients for each month.

3.2.d. The monthly evaporation rates were considered as inches of storage within the reservoir. The elevation at the top of the hydropower pool was chosen as the starting elevation from which to calculate equivalent reservoir storage volumes in terms of inches of evaporation. This elevation is the most conservative because it results in the most "volume" of evaporation.

3.2.e. The evaporation data was then converted to flow data in terms of equivalent storage within the reservoir. The Center Hill Reservoir storage-capacity tables "Cumberland River Basin, Center Hill Water Control Manual, Volume VIII" were used to determine day-second-feet (DSF) lost on a monthly basis. The quantity of DSF lost monthly was divided by the number of days in the month to determine a mean monthly daily flow in cfs lost through evaporation.

3.2.f. Converting the monthly evaporation data to flow data allowed a convenient means of applying the time distributed data to the hydrology model. This was accomplished by combining this flow data as a negative inflow into the reservoir.

3.2.g. Center Hill Reservoir was impounded in 1949. Sedimentation was considered in the design and was included in the construction cost. The sedimentation rate of Center Hill Reservoir is 0.5 acre-feet per square mile per year, obtained from Center Hill Dam and Reservoir: Reservoir Sedimentation Ranges Resurvey of August 1984 (December 1986). During a 100-year period, 108,700 acre-feet would be deposited within the reservoir between elevations 470 and 618.

3.3. Estimated Reservoir Inflows.

3.3.a. Objective and Scope. The objective of this work was to develop an inflow hydrograph to Center Hill Reservoir assuming the most severe drought conditions recorded occurred under existing conditions. The hydrologic models used for this work are existing models being developed for reservoir regulation by the Nashville District. The scope of this work was to develop the inflow hydrograph in the format necessary to utilize it in a water supply reallocation study on Center Hill Reservoir.

3.3.b. General. The Nashville District is developing the hydrologic models utilized for this work for use in reservoir regulation. **Table 5** lists the specific watersheds and their drainage areas that are contained in those models.

Table 5
Watersheds and Drainage Areas for
Center Hill Reservoir, Tennessee

Watershed	Type	Drainage Area (square miles)
Calfkiller River Below Sparta, TN	OBS	175.0
Collins River Near McMinnville, TN	OBS	641.2
Caney Fork at Rock Island	OBS	1,678.0*
Falling Water River Near Cookeville, TN	OBS	67.0*
Rain on the Pool	Calculated	36.0*
Caney Fork Local	Calculated	393.0*

* The sum of these watersheds equals 2,174 square miles, which equals the published value for the drainage area at Center Hill Dam.

3.3.c. Rainfall-Runoff Modeling. The Corps' computer program, HEC-1 "Flood Hydrograph Package," was used to develop the Center Hill Reservoir inflow hydrograph. HEC-1 produces a discharge hydrograph that represents inflow into the reservoir. This discharge hydrograph is a result of applying rainfall excess, or runoff, to a unit hydrograph. The unit hydrographs are developed by synthetic methods and calibrated to historic events by simulating observed events. Rainfall excess is essentially that portion of rainfall that can be observed in a stream as either baseflow or surface runoff. A significant portion of the volume of rainfall is either absorbed into the ground or vegetation. A modified version of HEC-1 was used to predict these transformations.

3.3.d. API Continuous Losses. The Antecedent Precipitation Index (API) method was used to determine rainfall loss rates for the drought simulations. This method was developed by the Nashville District to model continuous events on the Cumberland River and its tributaries. The API method of transforming rainfall to runoff is empirically based. Therefore, the matching of observed occurrences is

accomplished by using calibration techniques. The actual rainfall loss rate is based on the week of the year and the antecedent rainfall. The week of the year accounts for several physical processes such as temperature, evaporation rates, vegetation and hours of sunlight. The calibration of this model and its use in this study is discussed at the end of this section.

3.3.e. Historical Rainfall Information. Historical precipitation data for the drought analyses were collected from National Weather Service (NWS) data archives. The precipitation gages used in this study are within fifty miles of the local drainage basins. A total of fourteen gages were selected and collectively used to determine total continuous rainfall amounts and/or patterns for the years 1927 to 1997. The gages and their respective years of record available for use in this study are listed in **Table 6**. Rainfall records for all of the gages listed in **Table 6** were retrieved from CD-ROM's containing NWS records.

Table 6
Available Precipitation Gage Information Within
Fifty Miles of Watersheds Contributing
to the Center Hill Reservoir, Tennessee

Gage Name	Station Type	DSS Pathname	Type	Dates in Operation
Rock Island	Hourly	ROCKISL	Precipitation	1948 - 1962
Summitville	Hourly	SUMMIT	Precipitation	1948 - 1980
Monterey	Hourly	MONTEREY	Precipitation	1948 - Present
Altamont	Daily	ALTAMON	Precipitation	1948 - 1962
Cagle	Daily	CAGLE	Precipitation	1948 - 1980
Cookeville	Daily	COOKEVIL	Precipitation	1951 - Present
Falls Creek	Daily	FALLSCR	Precipitation	1949 - 1970
Gainesboro	Daily	GAINSBO	Precipitation	1948 - 1975
Statesville	Daily	STATESV	Precipitation	1951 - Present
Livingston	Daily	LIVINGS	Precipitation	1948 - 1991
McMinnville	Daily	MCMINNV	Precipitation	1927 - Present
Monterey	Daily	MONTERE	Precipitation	1948 - Present
Sparta	Daily	SPARTA	Precipitation	1948 - Present
Center Hill Dam	Daily	CENTERH	Precipitation	1948 - 1970
Rocky River	Daily	ROCKYRI	Precipitation	1949 - 1962
Smithville CAA AP	Daily	SMITHCA	Precipitation	1948 - 1954

3.3.f. DSS Database. All of the historical precipitation gage data records were entered into the Corps' DSS database system. The data were entered in regular time series format. The use of this database system allows direct input and output from many Corps' models such as HEC-1 and PRECIP. The modified version of HEC-1 used for this study (HEC1-API) makes use of the DSS database system.

3.3.g. Basin Average Rainfall. The Corps' computer program PRECIP was used to develop basin average rainfall for each of the watersheds. PRECIP computes area-average hyetographs from observed precipitation gage data. Like HEC-1, the program is designed for use with a DSS database. Rainfall at the centroid of each watershed is computed based on a weighted average of nearby rain gages. The gages are weighted based on the least distance squared from each watershed centroid. The daily basin average precipitation values for critical drought periods (discussed in later paragraphs) were computed by PRECIP and written into the DSS database. The computed values were then read directly into HEC-1 and transformed to inflow to the reservoir system.

3.3.h. Drought Investigations. Identifying the most severe drought for the area was the critical step in this study. Therefore, the development of a good historical database of rainfall was essential. For this study, drought investigations were conducted by first identifying continuous periods that were particularly dry for 3 to 4 months. A review of the historical record was made and all periods indicating possible drought conditions were identified. From this review, the driest years on record were identified. Of these droughts, the most critical to the Center Hill Reservoir was the 1953-1954 drought.

3.3.i. Rainfall-Runoff Model Calibration. Observed stream gage data must be available to perform any accurate type calibration on the HEC1-API models. Three gages were used to calibrate the HEC1-API models during drought conditions. The gages and their respective years of record available for use in this study are listed in **Table 7**. Flow records for all of the gages listed in **Table 7** were retrieved from CD-ROM's containing NWS records.

Table 7
Available Stream Gage Information
for Watersheds Contributing to the
Center Hill Reservoir, Tennessee

Gage Name	DSS Pathname	Type	Dates in Operation
Calfkiller River Below Sparta, TN	CALFKILLER RIVER BL SPARTA	Flow	1940 - 1971
Collins River Near McMinnville, TN	COLLINS RIVER NR MCMINN	Flow	1924 - Present
Caney Fork Near Rock Island, TN	CANEY FORK AT ROCK ISL	Flow	1911 - 1997

To calibrate the API parameters, the HEC1-API models were setup to represent the 1953-1954 droughts. Basin average precipitation for each event was applied to the watersheds, and the API parameters were varied until the calculated discharges matched the observed discharge data from the stream gages. In the model the gage on the Caney Fork near Rock Island, TN was calibrated using the other two gage sites.

3.4. Results

3.4.a. The calibrated HEC1-API model was used to determine an inflow hydrograph to the Center Hill Reservoir for the 1953-1954 drought. This hydrograph was written to the DSS database. The inflow hydrograph was utilized in the water supply reallocation study for Center Hill Reservoir.

3.3.b. When modeling for water supply usage, the return flows (if known) of the individual users were added to the inflows. Consequently, the total inflow hydrograph was increased to the benefit of all users of the reservoir.

3.4.c. The mean monthly evaporation rates (CFS) were represented as negative flows. The positive flows and negative flows were summed together and added to or subtracted from, depending upon the result being positive or negative, the inflow hydrograph. In some months this results in negative flows. This occurred in months when the inflows are less than the evaporation losses.

3.5. Area Capacity of Reservoirs.

The capacity data used for Center Hill Reservoir was taken directly from the "Cumberland River Basin, Center Hill Water Control Manual, Volume VIII". The data in that report was developed from 10-foot contour maps. The actual storage volumes were computed by the average end-area methods. The data in the survey report is tabulated in one-foot increments. Interpolation was used when necessary.

3.6. Storage Routing to Determine Water Supply Yield.

The modified Puls (level pool) storage routing method contained within the Corps' HEC-1 computer program was used.

3.6.a. To determine the storage for the fixed yield of Center Hill Reservoir, a routing was made for the worst of the drought events assuming no water supply usage. A continuous inflow hydrograph (a combination of inflow, leakage, and evaporation) representing the 1953 drought event was developed and input to HEC-1 using "QI" card format. The time ordinate for the withdrawals (negative) hydrographs was 21,600 minutes (15 days). The time interval for the inflow hydrographs was 60 minutes (1 hour). The computation period for the hydrograph routing was 1,440 minutes (1 day). Daily rainfall for the pool was calculated using the basin average rainfall of the Caney Fork Basin for the drought year and was input to compute the increase in water surface elevation resulting from rain on the pool.

3.6.b. HEC-1 allows reservoir storage areas to be input directly or to be computed by inputting surface area at various elevations. HEC-1 uses a conic method to compute storage volumes from provided surface areas. Because the storage values were developed using end-average methods, elevation-storage values were directly input into the model.

3.6.c. To complete the routing at each reservoir, a representative inflow and outflow must be provided. For the purpose of water supply yield analysis, three types of outflow were accounted for. The first source was evaporation. This outflow was accounted for by subtracting maximum monthly evaporation (converted to flow rates) from the continuous flow hydrograph. The second source of outflow was a combination of evaporation, leakage, and water quality or hydropower releases. The SL card was added to provide for a constant outflow of 90.0 cfs that represents the leakage. The third was a combination of evaporation, leakage, water quality or hydropower, and water supply average daily withdrawals in cfs for all M&I users. The withdrawals were entered into the DSS file as negative values, which the HEC-1 model adds to the inflow hydrograph.

3.6.d. To define the maximum impact of water supply upon the reservoir, the model was run for the drought period under all three conditions until a date was found at which the water surface began to steadily decrease below the hydropower pool. From this run of the drought period, the lowest elevation and date for all three conditions was also noted. The difference between elevations was calculated and storage-elevation tables were used to determine the number of acre-feet of storage required for water supply. The dates can be used to define impacts of water supply on lake levels with respect to time.

4.0. Impacts from Water Supply upon Center Hill Reservoir

4.1. The impacts from water supply upon Center Hill Reservoir were measured in four ways. First, the starting date at which the water surface elevation began to steadily decline was the same day as without water supply. Second, the lowest elevation reached during a critical drought was 0.5 feet lower than without water supply. Third, the lowest elevation date occurred 2 days later than without water supply. Fourth, the date at which the reservoir water surface elevation returned to the top of the power pool was 1 day later than the date without water supply. For Center Hill Reservoir the following impacts occurred:

	Date Water Surface Elev. Began to Steadily Decline	Lowest Elev. (Feet)	Date of Lowest Elevation	Date Water Elevation Returned to Top of Power Pool (648.0 feet)
With Evaporation Only	10 Oct	647.6	22 Nov	24 Nov
With Evaporation, Leakage, & Water Quality Or Hydropower	01 Aug	635.2	05 Dec	31 Dec
With Evaporation, Leakage, Water Quality or Hydropower, & Water Supply	31 Jul	634.7	06 Dec	11 Jan

Even during a severe drought, hydropower releases will be made at Center Hill Reservoir. The hydropower releases also serve the water quality function by maintaining a minimum dissolved oxygen level at Old Hickory Dam. As a result hydropower shares the impact of evaporation and sedimentation.

Evaporation Storage (ES) = 7,600 acre-feet
Water Quality and/or Hydropower and Leakage Storage (WQLHS) = 216,000 acre-feet
Water Supply Storage (WSS) = 8,500 acre-feet
Hydropower (HYDRO) = 492,000 acre-feet - WSS - WQLHS - ES
= 259,900 acre-feet

Portion of Evaporation Storage for Water Supply (WSE)

$$\begin{aligned} &= ES \times (WSS / (HYDRO + WSS + WQLHS)) \\ &= 7,600 \times (8,500 / (259,900 + 8,500 + 216,000)) \\ &= 133 \text{ acre-feet} \end{aligned}$$

During a severe drought, flood control is not an issue so flood control storage was not used to share the sedimentation pool.

Sediment Pool Storage (SPS) = $0.5 \text{ ac-ft/mi}^2 \times 2,174 \text{ mi}^2/\text{yr} \times 100 \text{ yrs}$
= 108,700 acre-feet for 100 years

Hydropower Storage, El. 648 (HS) = 1,330,000 acre-feet
Portion of Sediment Pool Storage for Water Supply (WSSPS)

$$\begin{aligned} &= SPS \times (WSS + WSE) / (HS - SPS) \\ &= 108,700 \times (8,500 + 133) / (1,330,000 - 108,700) \\ &= 768 \text{ acre-feet} \end{aligned}$$

Total Storage needed for Water Supply

$$\begin{aligned} &= WSS + WSE + WSSPS \\ &= 8,500 + 133 + 768 \\ &= 9,401 \text{ acre-feet} \end{aligned}$$

The above number of acre-feet is based upon withdrawals of 28.151 mgd and returns of 15.26 mgd. The amount of acre-feet per mgd is

$$9,401 \text{ acre-feet} / 28.151 \text{ mgd} = 334 \text{ acre-feet/mgd}$$